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COMPACT LUNAR POWER STATION

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GEORGE C. MARSHALL SPACE FLIGHT CENTER

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ABSTRACT

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One of the initial requirements for a manned lunar scientific base will be an adequate, dependable supply of electric power. Minimum weight and long operating capabilities necessitate the use of nuclear energy. McMurdo Sound Operations in the antarctic and the radar site in Sundance, Wyoming, have demonstrated the vast potential of nuclear power under severe operating conditions.

Application studies have been made on existing systems for nuclear auxiliary power (SNAP); however, these systems were not designed for large power output for extended periods and do not appear feasible. Therefore, an entirely new type of station should be designed and developed for the lunar environment.

The power requirements for such a station should be in the megawatt (electrical) range. A conceptual design of a compact lunar power station includes a partially-shielded, liquid-metal cooled, fast reactor heat source; a primary heat exchanger; a redundant potassium Rankine cycle turbo-electric generation system; and either a radiator or a lunar heat sink.

A modular-designed compact lunar power station becomes an immediate candidate for logistic missions utilizing the Saturn V Lunar Logistic vehicle. The technology exists for designing and developing a power station of this type; however, lead time spans up to 10 years and a research and development program should be initiated at an early date.

AUTHOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER

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Edward E. Dungan

ADVANCED STUDIES BRANCH
ASTRIONICS DIVISION

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SUMMARY

One of the initial requirements for a manned lunar scientific base will be an adequate, dependable supply of electric power. Minimum weight and long operating capabilities necessitate the use of nuclear energy. McMurdo Sound Operations in the antarctic and the radar site in Sundance, Wyoming, have demonstrated the vast potential of nuclear power under severe operating conditions.

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A modular-designed compact lunar power station becomes an immediate candidate for logistic missions utilizing the Saturn V Lunar Logistic vehicle. The technology exists for designing and developing a power station of this type; however, lead time spans up to 10 years and a research and development program should be initiated at an early date.

INTRODUCTION

The logical steps immediately following a successful landing and return of a manned lunar vehicle will initially consist of constructing and supplying a manned lunar scientific base. The steps to follow such an endeavor will be moon exploration, the establishment of a lunar observatory, and thus an orderly, well-planned progression of advanced scientific studies. To accomplish each of these, man must depend completely upon immediately available equipment within his established scientific base.

An adequate, dependable supply of electric power will be an initial requirement of the base. Such a power supply will not only support life within the base but also provide for work shops, laboratories, construction equipment, etc. It is apparent that a power station must be built that will meet all electrical requirements for five to ten years. Current technological trends indicate that a station of this magnitude can only be established through the utilization of a nuclear source.

Nuclear power has clearly demonstrated its capabilities at McMurdo Sound and military field locations (Ref. 1). Adequate power levels, dependability, long operating life, and minimum maintenance requirements necessitated the use of nuclear power in such remote areas. These same parameters become even more applicable to establishing a nuclear power station on the moon. The construction of nuclear power stations in remote locations has been accomplished through pre-manufactured packages or modules with assembly at the site. This concept must be followed in constructing the moon station since ease of assembly will be paramount.

A review of available designs reveals that a completely new type of station should be designed and developed for the lunar environment. This requirement is partly caused by a minimum weight design constraint. Other constraints that are not satisfied include the possible lack of water on the moon, assembly techniques, maintenance, and material problems. Application studies have been made on existing systems for nuclear auxiliary power (SNAP) (Ref. 2); however, these systems were not designed as stationary power stations and do not appear feasible. It should be noted that each of the several power stations now operating in remote locations were individually designed and developed to meet the minimum program requirements. Therefore, it can be asserted that present designs are not adequate for a useful lunar power station. The time required to design and develop a complete operating station of this type will probably be eight to ten years (Ref. 3). Thus, 1971 would be the earliest possible date that such a station could be made available. A review of various projected timetables indicates that the requirement for a lunar power station will be in the 1970-80 time period, primarily because of the availability of the Saturn V logistics and the Nova launch vehicles. To meet the above date lines, initiation of feasibility studies should be made in the near future.

POWER REQUIREMENT

The power requirement will determine the design of a lunar power station; therefore, a detailed study of the power needs over the initial five to ten years should be made. Other critical design parameters include power variations, emergency standby requirements, operational lifetime, and uprating capability.

An extensive study of the power requirements for a lunar power station has not been made for reasons such as uncertainty in base design and purpose. Until such details become known, the power requirements may only be estimated. However, feasibility studies such as "Project Horizon" (Ref. 4) have been made and have proven to be extremely useful. Approximately 500 watts, electrical, per man appears to be the minimum requirement to support life in an emergency. It can safely be assumed that a lunar base consisting of 100 men will require at least 1000 kilowatts electrical (kWe) to operate over a prolonged period. As exploration progresses and more sophisticated space experiments become operational on the moon, power requirements rapidly increase (Ref. 5).

The PM-3A (power reactor by Martin Co.), for example, operated at an average power of 1000 kWe during Deep Freeze 1962 and is expected to increase to 3000 kWe by Deep Freeze 1965 (Ref. 1). It should be noted that the winter complement at McMurdo Sound ranges between 150 and 300 men. Table 1 compares power requirements at remote bases with that of a lunar base. An important factor to be considered is that when power is available it will be utilized, as in the case of McMurdo Sound. Therefore, upgrading capability should be considered in the initial design.

TABLE 1. POWER REQUIREMENTS (REFS. 1 AND 4).

BASE	COMPLEMENT (Men)	POWER (MWe)
McMurdo Sound (PM-3A)		
Summer:	1000 - 1200	Deep Freeze 1962: 1.0
Winter:	150 - 300	Deep Freeze 1965: 3.0
Project Horizon	9	0.050
(Military Lunar Outpost)	12	0.115
	100	>1.0
Compact Lunar Power	100	2
Station (CLP-1)	1000	>5

Severe limitations of the upgrading capability in an optimum design may result. To avoid compromise, the initial design should be adequate for supporting at least a 100-man lunar base. As power requirements increase, additional power stations identical to the initial station may be added, thus providing a safety factor in case of a single station failure.

STATION CONCEPT

A lunar power station should be compact in design and will necessarily consist of three components; specifically, a nuclear reactor heat system, a heat transfer system, and a power generation and distribution system. The following parameters should be incorporated into the overall design.

1. Adequate power and efficiency
2. Minimum weight
3. Dependability
4. Long operating life (one year or more)
5. Transportable by Saturn V or Nova vehicles
6. Ease of assembly
7. Minimum maintenance
8. Automatic operation
9. Inherently safe - man rated.

FIGURE 1 illustrates schematically a possible concept for a compact lunar power station, including the three components previously mentioned. The nuclear reactor heat source is a liquid-metal cooled, fast reactor which is partially shielded and has a maximum operating power of 20 megawatts thermal (MWt). The primary coolant is molten lithium. The primary heat exchanger is of a conventional type. The heat transfer system operates on a potassium Rankine cycle and utilizes two turbines for dependability. The potassium loop is closed and, therefore, does not become radioactive through contamination. The power generation and distribution system is of conventional design and each generator produces a nominal power of 1.0 megawatt electrical (MWe) or a maximum of 2.0 MWe. The maximum overall power conversion efficiency of the station is 10 per cent.

A small auxiliary power supply may be required for startup, shutdown, and emergency interim periods. This power supply would most probably consist of batteries or fuel cells of nominal power.

A. NUCLEAR REACTOR HEAT SYSTEM

The selection of a reactor type is highly influenced by the minimum weight constraint, partly because of the transportability requirement. However, the weight of the reactor core is not necessarily the dominant component of the total system; the weight of the shielding and primary heat exchanger is an important factor. It does not appear feasible to utilize indigenous lunar materials for total shielding purposes for three major reasons: first, the composition of the lunar material

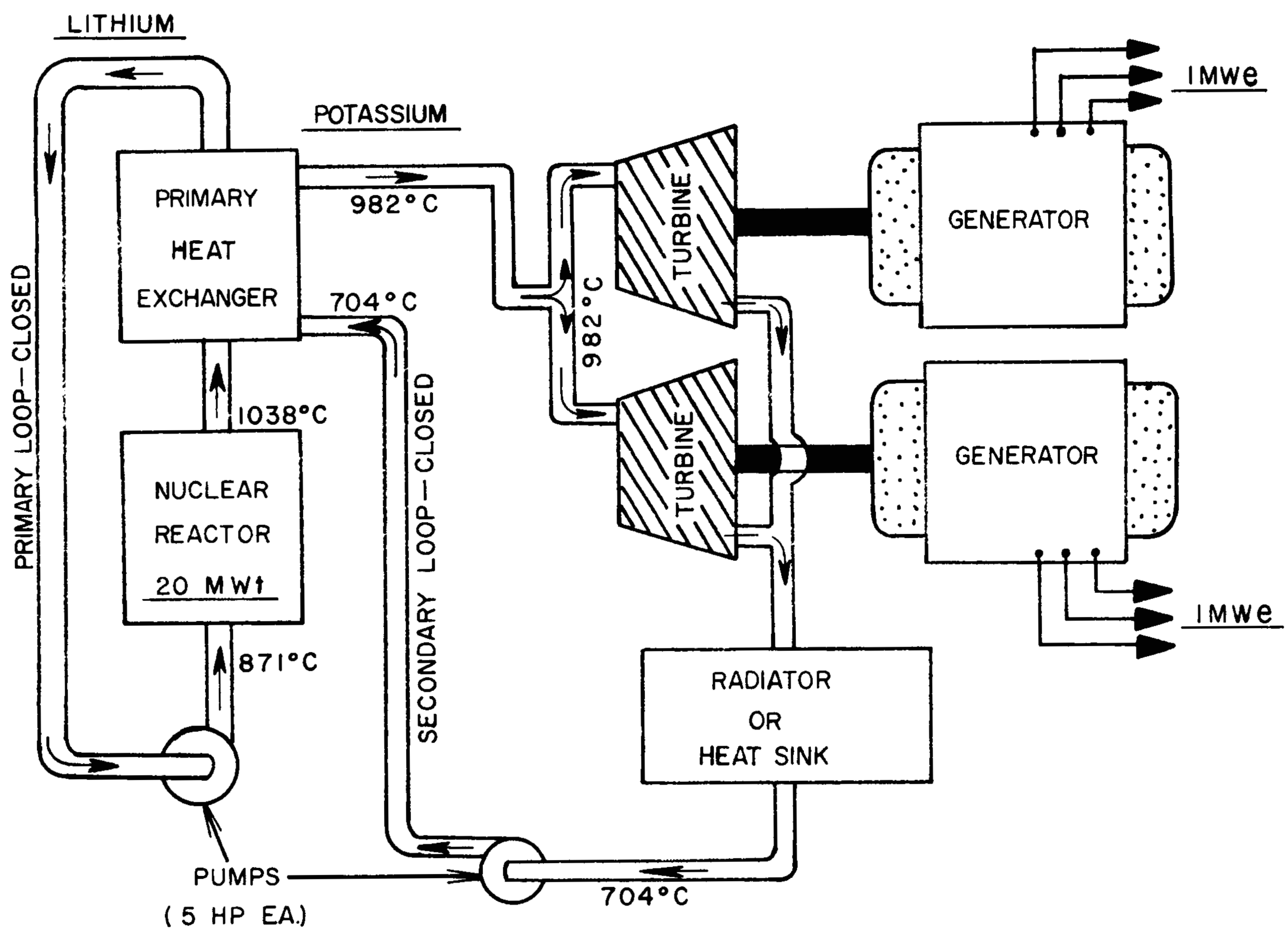

FIGURE 1. COMPACT LUNAR POWER STATION (2 MWe - 10 000 HOUR OPERATION).

is not known and the essential nuclear shielding characteristics are not predictable; second, the effect on control of the reactor is unpredictable; and third, the necessary mining tools and manufacturing machinery may not be available nor will time permit such an endeavor. The utilization of lunar terrain, possibly rock or granite, does not appear practical, especially if excavation is required. However, its use as a partial shield should be considered. In view of such restrictions, a thermal-type reactor is not considered feasible because of its large dimensions and, subsequently, the resulting excessive partial shield weight.

Implicit in the requirement for minimum size and weight of power conversion equipment is the necessity for a high primary coolant temperature at the reactor outlet. The reactor must also be capable of operating with a high degree of reliability with minimum maintenance for periods up to 10 000 hours or more under extreme conditions. In designing a reactor for such an application, only a fast or intermediate type should be considered. If the core of an intermediate reactor is to be as small as a fast-type reactor, reflector moderation must be employed. This generally results in a rather poor power distribution within the core and has no obvious compensating advantages. The fast-type reactor emerges as the most likely candidate for further consideration.

The selection of a primary coolant offers four plausible choices: pressurized or supercritical water or other liquid, boiling water or other liquid, gas, and liquid metal or salt. The boiling liquid system can be eliminated immediately because of the large pressure shell required to contain the vapor phase within the reactor pressure vessel. Of the remaining three, the liquid metal or salt cooled system results in appreciably smaller core dimensions and operates at low pressure rather than at 136 to 204 atm. In addition, the liquid metal or salt system offers the potential of operating at much higher temperatures with resultant improvement in power conversion equipment efficiency and weight as previously noted. A maximum potential for power plant growth is obtained by using a liquid metal or salt system through increasing power output without increasing the core size.

The choice of liquid metal in preference to molten salt is desirable for three reasons: first, metals are inherently better heat transfer media; second, liquid metal technology is further advanced; and third, reactor startup problems are simplified. Of the numerous liquid metals to be considered as reactor coolants, three appear potentially useful for high temperature lunar application. These are lead-bismuth eutectic (liquid from 121° to 1670°C), sodium (liquid from 98° to 883°C), and lithium (liquid from 179° to 1317°C). In addition to a very low vapor pressure, the Pb-Bi eutectic has a relatively high specific gravity and low specific heat which results in high pressure head and large mass flow; therefore, it should be eliminated. The principle advantages of sodium, as compared with lithium, would appear to be the vast background of operating experience, compatibility with stainless steel, high thermal conductivity, high vapor pressure, and slightly low melting point. The principle advantages of lithium are low density, high specific heat, and particularly high boiling point. Although lithium is incompatible with most metals, it appears that columbium alloys will be adequate at the temperatures and velocities considered (Ref. 6). A comparison of the various pertinent properties of lithium and sodium is shown in Table 2.

TABLE 2. PROPERTIES OF LITHIUM AND SODIUM.

PROPERTY	LITHIUM	SODIUM
Melting point	179°C	98°C
Boiling point	1317°C	883°C
Density	0.48 g/cm^3	0.83 g/cm^3
Heat capacity	1.0 cal/g-°C	0.3 cal/g-°C
Thermal conductivity	0.08 cal/s-cm-°C	0.16 cal/s-cm-°C
Thermal neutron absorption cross-section	Li-65, Li^6-945 Li^7-0.33 barns	0.45 barns
Pumping power for equivalent heat removal for °C temperature rise	3.41	34
Vapor pressure at 1038°C	4 mm Hg	1500 mm Hg

A conceptual lithium-cooled, fast reactor design applicable to lunar power stations is shown in FIGURE 2. Pin-type fuel elements are recommended because of their high surface-to-volume ratio. Fuel would be highly enriched uranium oxide in the form of cermet bonded to the pin walls or as uranium oxide pellets within a fluid thermal link. The core would be a cylinder with a diameter and active length of approximately 25 cm. The reflector could be hafnium which is also an excellent primary gamma shield. Control would be performed by rotation of encircling drums which are located within the hafnium shield-reflector. Rotation of these drums varies the thickness of reflector material between the core boundary and the boron-carbide "neutron traps" within the drums. Care should be exercised in the

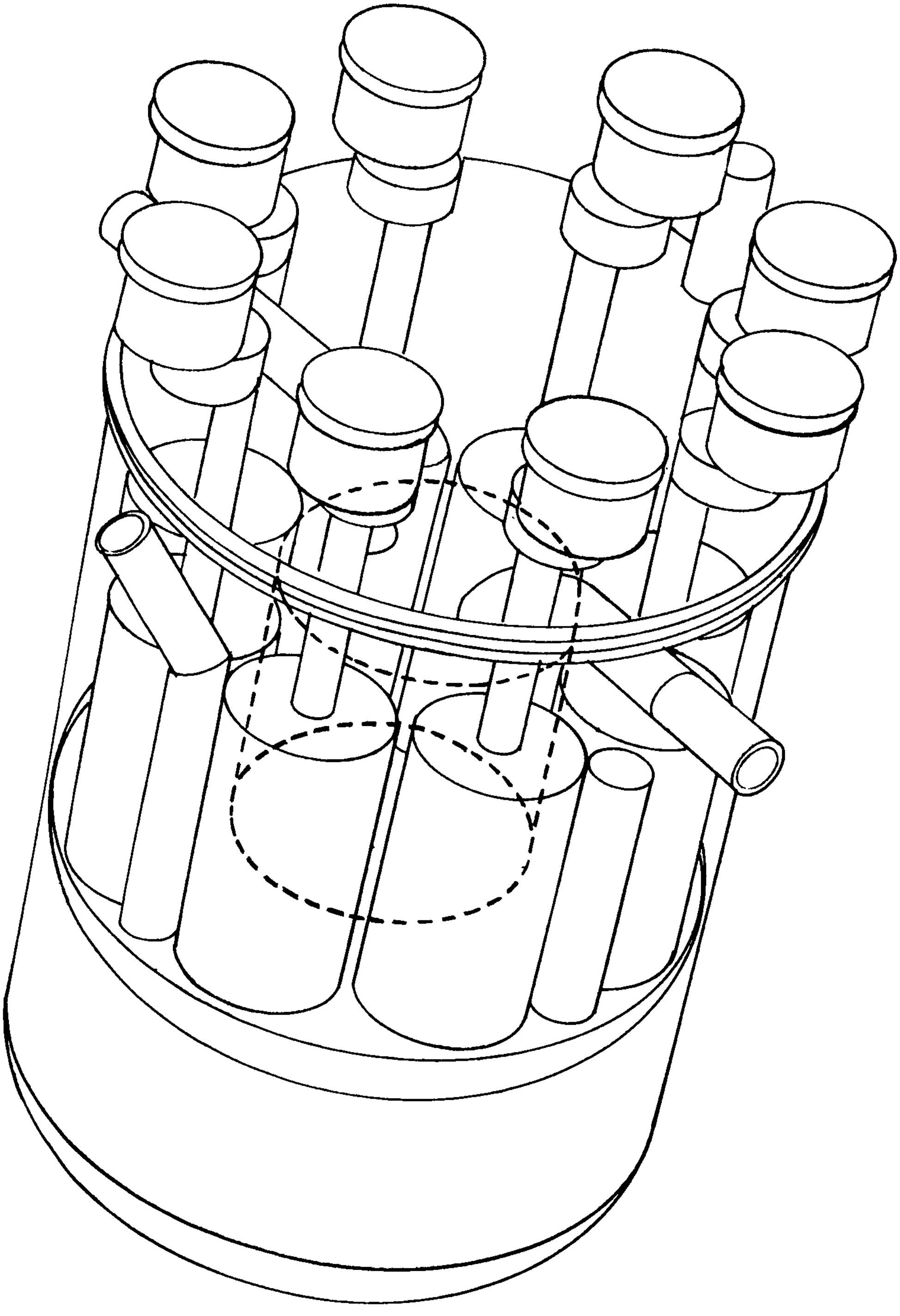

FIGURE 2. LITHIUM-COOLED FAST REACTOR CONCEPT.

design of such systems to insure that transient positive temperature coefficients of reactivity cannot occur because of thermal expansion. Structure and coolant pipes could be stainless steel, clad with a suitable columbium alloy.

The minimum weight constraint justifies a rigorous shield-reflector design. A typical assembly is shown in FIGURE 3. A "modified" unit shield concept is employed for illustration purposes to constrain the radiation dose rates to acceptable low levels in all directions. The shield consists of four principle elements: primary gamma shield-reflector, first neutron shield, secondary gamma shield, and second neutron shield which may or may not consist of lunar material.

The primary gamma shield should be a dense material such as hafnium and its purpose would be to attenuate gamma rays born in the core and also to reflect fast neutrons for reactor control. The location of the primary gamma shield immediately outside the core also exploits the geometric advantage of low weight for a given thickness. However, since there is a strong neutron flux present in the primary gamma shield, secondary gamma rays originate through inelastic and capture processes. Therefore, all the heavy gamma shield cannot be located immediately outside a fast core. Consequently, the primary gamma shield should be reduced to a size less than that required in the absence of secondaries, and a layer of neutron shielding should be inserted between it and a subsequent layer of gamma shielding. This second gamma shielding layer provides the additional attenuation needed for the primary gamma rays as well as that required to attenuate those secondaries produced in the primary gamma shield by neutrons. Its location and type of material would be determined through an optimization procedure. Both layers of gamma shielding should contain boron to suppress thermalized neutrons which result in capture gammas. Among other factors, the additional two neutron shielding layers should be of very low atomic number, such as lithium-hydride if lunar materials are not available.

B. HEAT TRANSFER SYSTEM

The heat transfer system of the conceptual design consists of two closed loops plus an auxiliary shield coolant loop if needed. The primary closed loop utilizes lithium in a molten state as a coolant for the reactor and as a heat transfer medium to the primary heat exchanger. The selection of molten lithium as the primary coolant was previously discussed. The secondary closed loop utilizes potassium as a heat transfer medium and was selected on the basis of the Rankine cycle power conversion system (Ref. 3).

The primary coolant enters the pressure shell at approximately 871°C through two channels and is directed through the shield and reflector, thus cooling the high temperature sections. It then enters a plenum

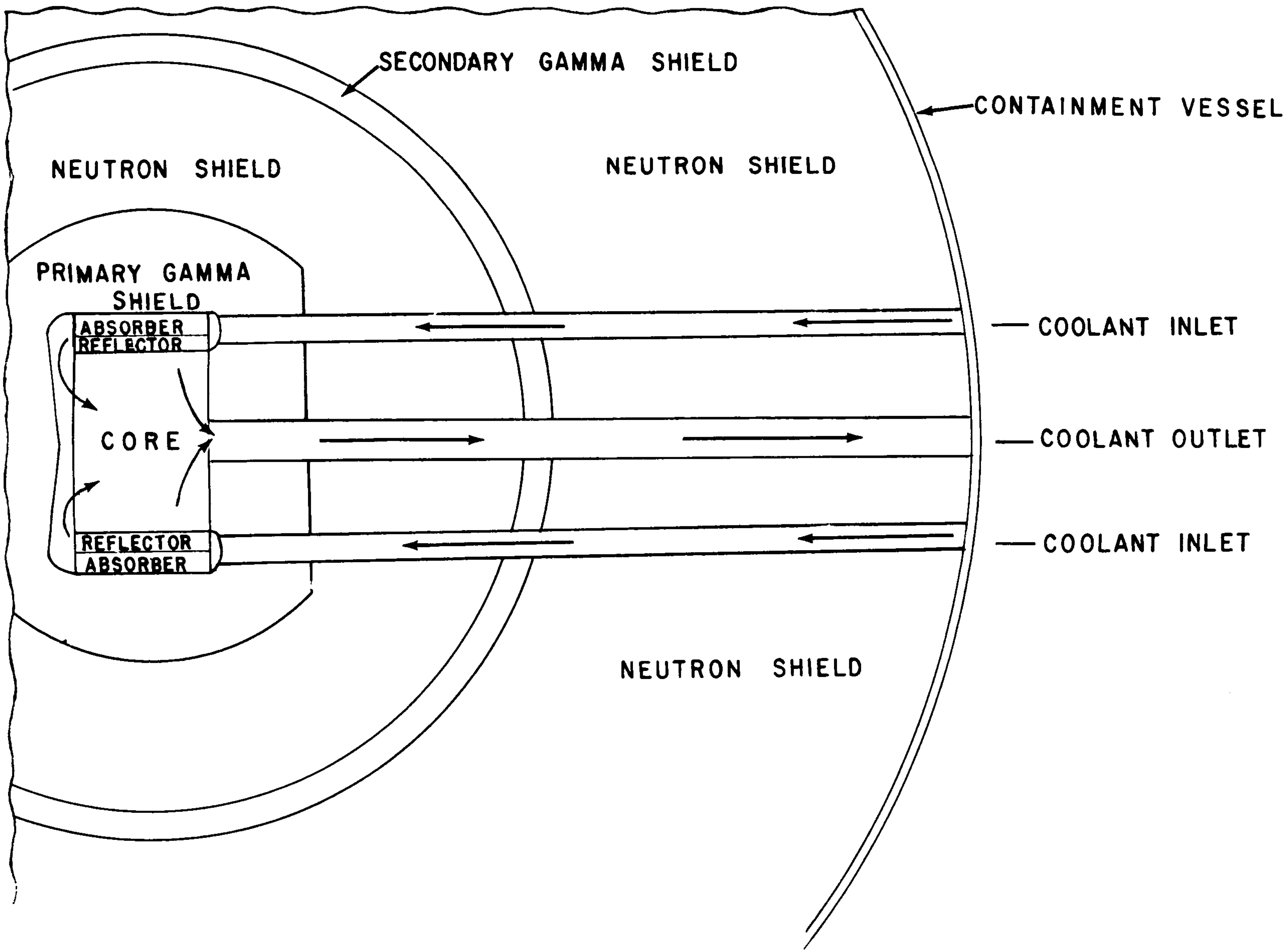

FIGURE 3. SHIELDING SCHEMATIC.

chamber and passes through the core reaching an outlet temperature of about 1038°C. The temperature is reduced to approximately 871°C as the lithium passes through the primary heat exchanger and primary coolant pumps and back to the reactor.

The secondary coolant, potassium, enters the primary heat exchanger in a liquid state at approximately 704°C and its temperature is increased to about 982°C. It then passes through the turbines as a gas, thus driving the generators. A heat sink will probably be necessary to condense the gas before it reaches the pump where it is again pumped through the primary heat exchanger. Since the lunar surface temperature does not exceed 150°C and the gas temperature is about 982°C, the temperature differential is rather large; therefore, contact with the lunar surface may serve as an adequate heat sink.

Auxiliary cooling of the surrounding reactor shield may be necessary to avoid damage within the pressure vessel. Alkylbenzene-350 could be utilized since the coolant temperature should not exceed 315°C; it is also an excellent neutron shielding material in itself.

The pumping speed of the primary lithium coolant would be a function of the core design as well as the heat exchanger design. The pumping speed of the potassium secondary heat transfer medium would not only be a function of the primary system but also of the turbine efficiencies, etc., of the Rankine power generation cycle. Existing technology could be utilized and there should be relatively few developmental factors other than coolant corrosion of turbine blades and pumps.

C. POWER GENERATION SYSTEM

The power generation system may possibly consist of two sets of turbines and generators for each reactor heat system. The purpose of two independent sets would be to provide operational dependability as well as power efficiency. Each system operates on a potassium Rankine cycle because it offers a high conversion efficiency and operates at relatively low source temperatures. The Brayton cycle, which is a gas cycle, becomes unattractive because of its lower fraction of Carnot efficiency and high reactor temperature requirements (Ref. 7). The megawatt output results in an overall system efficiency of 10 per cent if calculated on the basis of an optimum Carnot of 25 per cent and a conversion efficiency of 40 per cent of Carnot. To minimize the system weight, it is necessary that the conversion system operate at a high sink temperature and recover a maximum fraction of Carnot efficiency (Ref. 8). State-of-the-art development methods for the potassium Rankine cycle are available through such projects as SNAP-50 (Ref. 6). Turbine design and development appears as the most formidable problem primarily because of coolant compatibility at operating temperatures for extended periods.

The development of an efficient, dependable 2 MWe power generation system will probably be a relatively minor project when compared with the reactor and heat transfer systems. However, an integrated design will be essential to obtain an optimum overall lunar power station design.

PROBLEM AREAS

To anticipate the precise technical areas requiring developmental work is impossible; however, it is anticipated that a majority of such problems will lie in the nuclear and heat transfer fields. Some of these and other problems are summarized below.

A. NUCLEAR AREA

Critical experiments will be required to determine fuel inventory, reactivity, flux distribution, control element effectiveness, and temperature coefficient of reactivity. Determination of corrosion and heat transfer in high temperature liquid metal areas will be necessary as well as development of fuel element lubrication techniques and development of fabrication techniques for unusual engineering materials.

Controls and instrumentation problem areas include development of drive mechanisms for reactor control drums, pumps, and valves, and development of ruggedized electronic components of radiation instrumentation and control computers.

The shield-reflector design will present a challenging array of problems associated with weight optimization as well as fabrication and integrity at the operating temperatures and radiation levels being considered. Weight optimization parameter is highly dependent upon the design dose rate constraints and the maximum single component weight allowable for earth-to-moon logistics. However, the tremendous amount of experimental data available from previous aircraft nuclear propulsion and mobile power plant programs should be adaptable to the compact lunar power station concept, primarily because of the extreme similarity of design parameters.

Assembly techniques utilized at remote sites, such as McMurdo Sound, may be adaptable to the lunar station since the available time for such a manned operation and the unavailability of conventional equipment will necessitate a minimum of manual operation. Automatic checkout, startup, and operation is highly desirable.

B. HEAT TRANSFER AREA

The primary problems associated with the heat transfer area include determination of both primary and secondary coolant distribution, development of suitable pumps and values with particular attention to seals and bearings, stress and creep of structural components at high temperatures, turbine blade design, and corrosion of components within the loops. Flow rate determinations and the primary heat exchanger design will require an integrated effort and may become an influencing system design factor.

The utilization of lithium as the primary coolant and heat transfer medium is justifiable for a number of reasons, and previous experimental data indicate that columbium cladding solves the corrosion problem at high temperatures. Potassium is a suitable heat transfer medium when used in the Rankine cycle; however, the wealth of experimental data on the eutectic, NaK (sodium-potassium), may warrant additional consideration.

C. LUNAR ENVIRONMENT

The remote sites at which nuclear power stations have been constructed present strikingly similar environmental problems for manned operation. The lunar environment includes the additional problem of high vacuum as well as meteorites, space radiation (both charged particle and electromagnetic), and unknown surface characteristics. However, these environmental problems are not restricted to the construction of a nuclear power station; rather, they are to be encountered in the construction of any type of power station on the moon.

CONCLUSIONS

A review of studies that result in modifying existing nuclear power plant designs reveals a number of significant reservations; notably, the method of reactor control, shielding, and weight optimization. A designer's primary prerequisites include physical properties and nuclear characteristics of the materials of interest. Since such data are not available for lunar materials, their initial utilization would be undesirable. Even if such data became available within the next few years, methods of extraction and fabrication on the moon do not exist. If the lunar surface is rock or some other hard material, it does not appear practical to excavate extensively during the early exploratory years.

Such problems appear to necessitate a modular-designed nuclear heat source. Consequently, a small, light weight, liquid-metal cooled, fast type reactor becomes the leading candidate. The technology exists for designing and developing a power system of this nature. However, lead time spans up to 10 years and initiation of such a research and development program becomes highly important at an early date. It most definitely should not depend upon adaptation of such systems as present day remote power stations or advanced SNAP systems. Table 3 shows a comparison of space power systems including the conceptual CLP-1.

TABLE 3. COMPARISON OF SPACE POWER SYSTEMS (REFS. 2, 3, 6, AND 8).

SYSTEM	AVAILABLE	POWER (kWe)	SPECIFIC WEIGHT (kg/kWe)	UNSHIELDED WEIGHT (kg)
SNAP-2	1965	3	90.8	272
SNAP-8	1966	30	22.7	680
		60	28.7	1725
		120	17.4	2090
		180	15.1	2715
SNAP-50	1970	300	4.5	1360
		1000	4.5	4540
CLP-1	1970-80	2000	2.7	5454

A modular-designed complete lunar power station becomes an immediate candidate for early logistics missions utilizing the Saturn V Lunar Logistics vehicle (LLV). One LLV would be sufficient for the nuclear heat source and the primary heat exchanger modules while an additional LLV could transport the remaining modules of a minimum weight system. Table 4 gives an estimated weight summary of the conceptual CLP-1. The heaviest single component would be the core-shield-reflector assembly which has a maximum weight of 9310 kg. If transportation of a maximum auxiliary (neutron) shield was required, it could be manufactured in segments of 4540 kg or less and thus be readily transportable by one or more LLV's.

TABLE 4. CLP-1 ESTIMATED WEIGHT SUMMARY.

MAJOR COMPONENTS	WEIGHT (kg)
Nuclear Reactor Heat System	
Core (bare)	230
Reflector-shield and control drums	2270 to 9080
Auxiliary (neutron) shield	13 600
Subtotal - - - - - - - - -	-2500 to 22 910
Heat Transfer System (including primary heat exchanger, lithium and potassium coolants, pumps, and miscellaneous)	454
Power Generation and Distribution System	
Turbines (2)	137
Generators (2)	1455
Radiator or heat sink	454 to 3190
Miscellaneous	454
Subtotal - - - - - - - - -	-2500 to 5236
TOTAL	
Minimum	5454 or 2.7 kg/kWe
Maximum	28 600 or 14.3 kg/kWe

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Edward E. Dungan

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

Fred E. Digesu

FRED E. DIGESU
Chief, Advanced Studies Branch

W. Haeussermann

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